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Automated Tool for the Comparative Estimation of Earthmoving Productivity

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Abstract: This paper presents an automated tool for comparative estimates of earthmoving productivity, focusing on excavation operations. The developed system includes three modules (computational, data storage, operational) and a series of forms that estimate construction productivity for three types of equipment (excavator, loader, truck) based on fourteen estimation methodologies. To the authors' best knowledge, it is the first research attempt at developing an automated tool based on the comparative evaluation of such a diverse set of estimation methodologies. All system components have been developed in a Microsoft (MS) environment, thus taking advantage of their user-friendly nature. A numerical example corroborated the tool's validity. Future research may optimize the module integrated into the developed application to assist construction estimators in reaching informed decisions when deploying critical project resources.

Keywords: Construction productivity, estimation, excavation, statistical analysis.

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1. Introduction

The expected output per time unit (hour or day), usually termed productivity, affects, to a large extent, the cost and the duration of a construction project. The on-site managerial decisions and the dynamically changing operational conditions play a critical role in deciding the construction technique and improving the efficiency of operations. In that respect, the accuracy of estimating equipment-intensive productivity is an important factor for both the schedule and cost programming of construction projects. The inability to objectively estimate construction productivity due to the large variety of estimation methodologies and their integrated parameters depends merely on the experience of the engineer or cost estimator involved in the process. Therefore, the estimator should be in a position to know (a) what key operational factors affect productivity, (b) what is the extent of their variability, (c) in which way they influence the output of the selected productivity methodology, and (d) which methodology is best suited for the analysis of the particular construction case.

In essence, there are two alternatives for estimating construction productivity: (i) data-oriented and (ii) process-oriented methodologies (Zayed and Halpin, 2004; Yi et al., 2022). In the case of past historical data being available, the data-oriented approach is followed by applying statistical regression models (Molaei et al., 2022) or artificial neural networks (Ahmed et al., 2022) or simulation and enhanced visualization techniques (Kim and Chi, 2020). On the other hand, when a new construction technique or equipment is applied, no such data is available, leading to the application of generic, process-oriented methodologies (Chen et al., 2022). These methodologies stem from (a) equipment manufacturers' manuals, (b) editions from contractors' associations or individual researchers, and (c) textbook editions. The present research focuses on developing an automated system to estimate construction productivity for three types of equipment (excavator, loader, truck) based on the process-oriented approach's fourteen estimation methodologies. Although similar tools and scientific approaches for earthmoving operations have been developed in the past (Alzubi et al., 2022; Chen et al., 2022; Mohsenijam et al., 2020;), it is—to the authors' best knowledge—the first research attempt to develop an automated tool based on comparatively estimating such a diverse set of methodologies.

The structure of the paper is as follows: initially, the fourteen estimation methodologies are briefly presented, followed by basic theoretical concepts for the database management system development. Consequently, the research methodology is described, in a step-wise fashion, in order to explain the automated tool development process. Finally, a case study is presented to corroborate the tool's validity by replicating theoretical estimates through the use of the developed database management system.

2. Background

2.1. Productivity Estimation Methodologies

The estimation methodologies that have been incorporated in the analysis have been published in equipment manufacturers' manuals (Caterpillar, 2019; Komatsu, 2013; Liebherr, 2003; Volvo, 2015), editions from contractor's associations or individual researchers in Germany (Bauer, 2007; BML, 1983; Garbotz, 1966; Girmscheidt, 2010; Hoffmann, 2006; Huster, 2005; Kotte, 1997; Kuhn, 1984), and textbook editions (Nunally, 2007; Peurifoy and Schexnayder, 2002). It should be noted that published research which is loosely based or derived from the aforementioned publications has been excluded from the study for brevity reasons (e.g., Edwards and Holt, 2000). In essence, the factor model (Thomas and Yiakoumis, 1987) is adopted, which distinguishes between the theoretical (Q_{th}) and the effective productivity (Q_{eff}). The theoretical productivity represents the optimum productivity rate under ideal operational conditions, while the effective productivity expresses an adjustment of the theoretical productivity under the influence of the actual on-site working conditions. In earthmoving operations, the mathematical model that converts Qth to Qeff takes into account a series of multipliers that represent the so-called productivity factors, as summarized below in Eq. (1) (Panas and Pantouvakis, 2010; 2015):

$$Q_{eff} = Q_{th} * \prod f \quad (1)$$

where (in order of appearance): Q_{eff} = effective excavation productivity [m^3/h]; Q_{th} = theoretical excavation productivity [m^3/h]; Πf = productivity factors that are diversified according to the applied estimation methodology.

The reader is referred to Panas et al. (2022) for further details on the theoretical assumptions of the utilized methodologies for brevity reasons.

2.2. Automated Tool Design

The proposed automated estimation tool is developed along the philosophy of a database management system (DBMS) whose structure has been shaped in such a way so as to (a) include the least possible data in order to save storage space, (b) ensure the validity of multiple data entries and (c) preserve data independence, in the sense that upon any amendment in user requirements, the system can be adjusted accordingly without changing the data structure. The system is essentially a relational database, where the normalization technique has been applied in all system components (Moselhi and Marzouk, 2000).

The MS Excel software has been used as a template for developing the software system. The selection is justified by its user-friendly layout and its possibility to conduct programming sequences through the Visual Basic (VBA) add-on feature, where the user may create additional tools to visualize the system's components.

2.3. Cognitive Gaps to be Addressed

Given the aforementioned factors, the main research objective is to bridge the gap between the estimator's experience in estimating works and the objective complexity of applying different methodologies based on theoretical assumptions that occasionally contradict one another. In that sense, the main research questions are as follows:

- In which way may an estimator acquire an informative notion of a planned construction activity's variability in the expected productivity output?
- How can different productivity estimation methodologies be incorporated into a seamless digital framework?
- What are the critical input parameters that have to be defined by the user?
- How can the productivity output's validity be cross-checked and enhanced?

All these research questions will be addressed within the framework of a database system specifically developed to satisfy the research needs.

3. Research Methodology

3.1. System Architecture

The automated tool integrates all cost and productivity parameters of the studied estimation methodologies. The parameters are categorized into groups in case they share common characteristics. The productivity estimate is executed along with the users' input data. Each methodology is run separately, and the results are presented in tabular format. If insufficient input data are provided for any methodology, then no results are produced for that method. In that case, the specific methodology (or combination of methodologies) is excluded automatically from the analysis and is not included in the yielded results table. Each user may select which methodologies to include in the analysis. The users interact with the system through an interface whose main constructs are illustrated in Fig. 1 below. The next section analyzes each proposed system component.

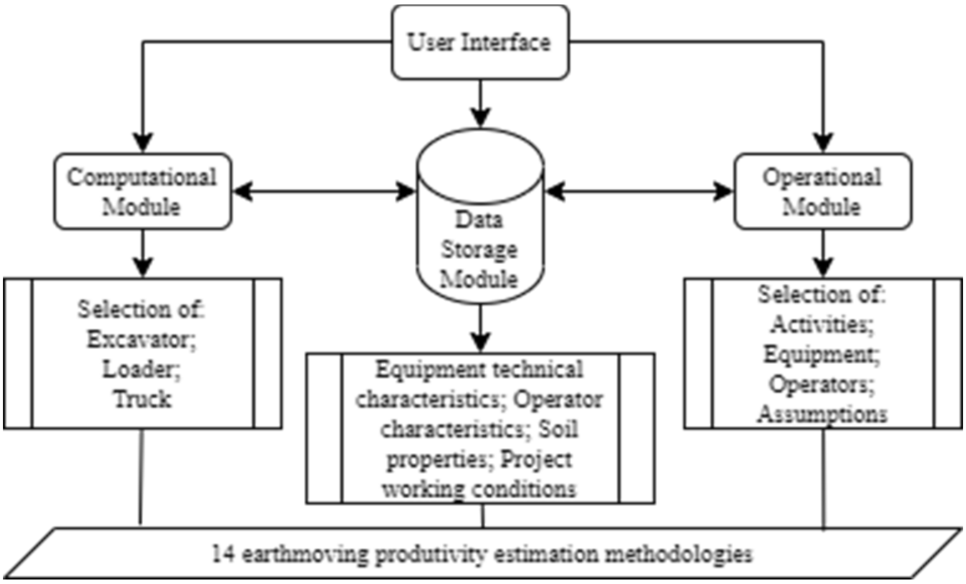


Fig. 1. The main constructs of the proposed system

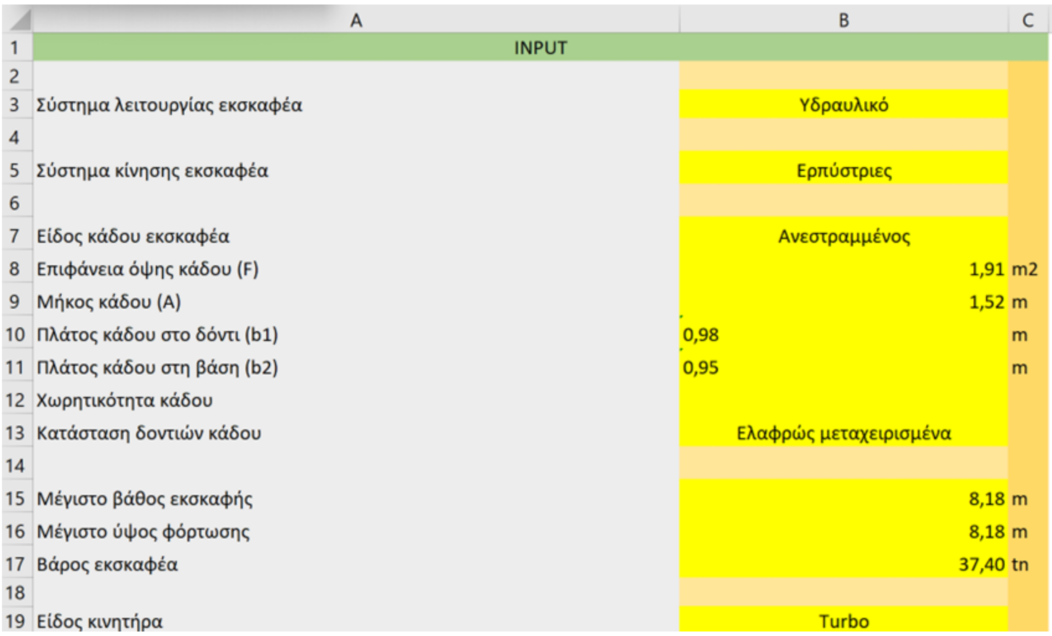
3.2. Research Limitations

This automated tool reflects a deterministic approach on estimating construction productivity. No enhanced modeling techniques are adopted (e.g., simulation) and the analyst can comprehend the analysis easily. The reason is to serve the main research objective, which is proving the approach's conceptual value. However, the system can easily expand to include (a) more construction machinery and equipment, (b) more estimating methodologies and (c) additional productivity factors or critical input parameters. In addition, the developed tool is limited to the excavator-truck system; however, the analyst can add more estimation methodologies if the estimator knows their theoretical assumptions.

4. System Components

4.1. Computational Module

The computational module of the automated tool uses three spreadsheets, one for each equipment type (excavator, loader, truck). Each spreadsheet includes two tables (see Fig. 2). The first table includes all input data to estimate productivity according to each methodology. The second table includes fourteen lines, representing the fourteen estimation methodologies included in the analysis. The executed calculations include complex formulas, logical functions, data mining from tables, and value estimates from empirical graphs. The system uses the software's enhanced capabilities to execute complex mathematical formulas and upgrade logical functions. Each cell of the first table is connected to one or more cells of the second table and yields productivity estimates through a series of calculations.



	A	B	C
1	INPUT		
2			
3	Σύστημα λειτουργίας εκσκαφέα	Υδραυλικό	
4			
5	Σύστημα κίνησης εκσκαφέα	Ερπύστριες	
6			
7	Είδος κάδου εκσκαφέα	Ανεστραμμένος	
8	Επιφάνεια όψης κάδου (F)	1,91	m2
9	Μήκος κάδου (A)	1,52	m
10	Πλάτος κάδου στο δόντι (b1)	0,98	m
11	Πλάτος κάδου στη βάση (b2)	0,95	m
12	Χωρητικότητα κάδου		
13	Κατάσταση δοντιών κάδου	Ελαφρώς μεταχειρισμένα	
14			
15	Μέγιστο βάθος εκσκαφής	8,18	m
16	Μέγιστο ύψος φόρτωσης	8,18	m
17	Βάρος εκσκαφέα	37,40	tn
18			
19	Είδος κινητήρα	Turbo	

Fig. 2. Excerpt of estimation tables utilized in the proposed system

Apart from the formulas, the scrutinized methodologies use tables and respective graphs. Due to their small size and structure, most tables can be transformed into logical formulas and calculated with the same method. On the other hand, the graphs must first be transformed to tables to calculate the productivity estimates. Twenty different graphs were transformed to thirty tables with 13.264 datapoints. These tables have been inserted into the database and are accessible by any estimation methodology during the data insertion phase.

Each methodology's productivity factors do not always have single values. They may have a range of a minimum and a maximum values, and the user has to select a value in between. The system automatically selects the minimum, average, and maximum value of each productivity factor and the user may define a fourth value within the designated range, yielding four productivity estimates: minimum (Qmin), average (Qmid), maximum (Qmax) and the user-defined values (Qset). With the input data points, the system instantly calculates the respective productivity values.

4.2. Data Storage Module

After the computational module is activated, all data are stored in the system's databases. There are four data storage categories:

- Technical characteristics of each piece of equipment.
- Operator characteristics.
- Soil properties.
- Project working conditions.

Most of the fields referring to the equipment and operators usually have constant values. On the other hand, fields associated with soil properties and project working conditions are assigned different values. For example, a construction company with permanent personnel and a specific equipment fleet should register the same values for the equipment's technical characteristics and the operators' capacity for its entire project portfolio. However, the latter is differentiated depending on each project's soil characteristics and working conditions.

Two databases (one for the equipment and one for the operators), where the respective values are registered in tabular format, help users operate the system. The latter can be retrieved and used by the computational system module. Specifically, the system includes four tables corresponding to four spreadsheets in Excel, which are used for registering all equipment related data. The first table (labeled "EQUIPMENT") includes fields describing equipment such as unique code, equipment type, manufacturer, model, license plate etc. The other three tables (i.e., "EXCAVATOR," "LOADER," "TRUCK") connect to the first table through a unique code. They include fields corresponding to the equipment's technical characteristics. Similarly, the operators' data are registered in three tables which correspond to three spreadsheets in Excel (labeled "OPERATORS," "EXCAVATOR OPERATORS," and "LOADER OPERATORS"). The first table includes the general data of the operators (i.e., unique code, surname, name, social security number, equipment type, etc.), while the other two tables connect through a unique code to the first table and contain data relating to the operators' skills.

4.3. Operational Module

The operational module has two objectives: 1) to offer a more user-friendly working environment and 2) to act as a DBMS. It used VBA programming and includes seventeen forms and 237 data input fields. The system is activated by clicking on the main form, which includes a dropdown menu with four choices (i.e., Activities, Equipment, Operators, Assumptions). The menu "Activities" allows users to initiate a new work description or exit the system. The menu "Equipment" activates the equipment database, allowing the viewing, adding, editing, or deleting of equipment. The same goes for the menu "Operators." The menu "Assumptions" is associated with the basic productivity assumptions for each activity. More specifically, the user chooses the values of the productivity factors, namely the minimum or maximum value or any other user-defined value in between.

By choosing "Activities" → "New Activity," the main "work form" is activated. This form is divided into two parts: the first part helps the user choose the equipment, define the productivity factors, and select one or more estimation methodologies. The second part of the form contains a four-page window: (a) equipment selection, (b) excavator productivity estimation, (c) loader productivity estimation, and (d) truck productivity estimation. Once a specific piece of equipment is selected, the respective page for that equipment is activated, with all equipment characteristics reset to null. If the user chooses the button "Select from Database," then the "Equipment" database is activated, which contains all registered equipment and their operators (see Fig. 3 below). Pressing the "Select" button will automatically register the equipment and the operator characteristics in the new project. The productivity estimation tables (excavator, loader, truck) rely on the user inputting the data. The productivity estimate is automatically executed, and the results are presented on the same screen in the lowest right corner (as shown in Fig. 4).

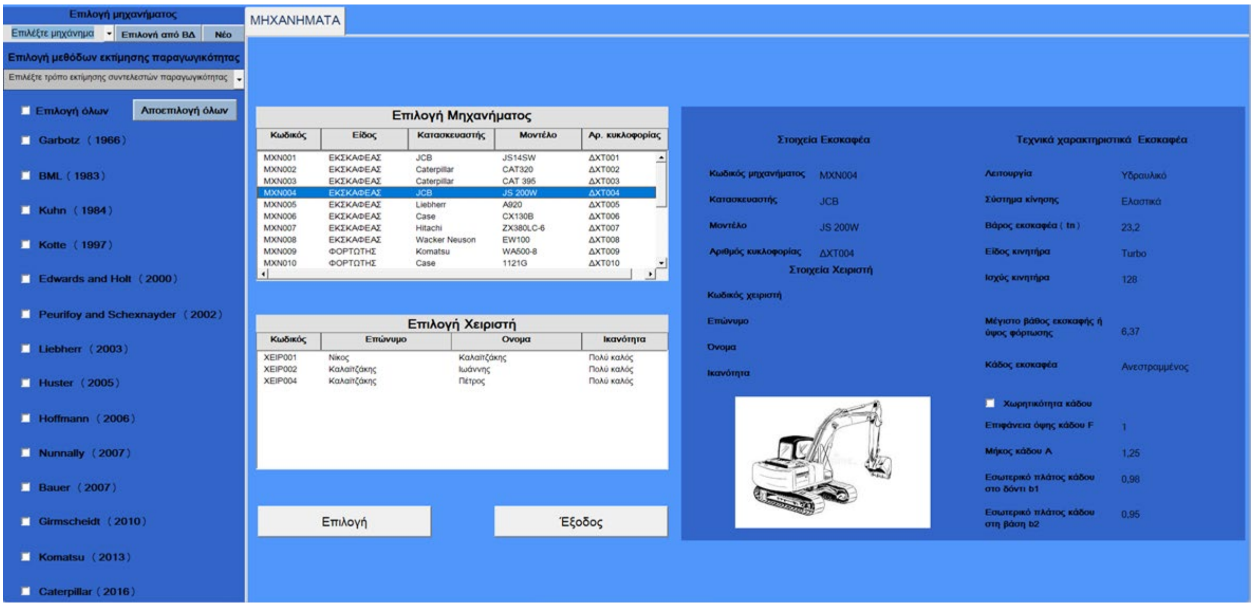


Fig. 3. Equipment and operator type selection form

Before inputting the data and generating the results, there are two sanity checks. The first comprises logical checks, i.e., whether all fields are completed, if at least one estimation methodology has been selected, etc. The second comprises all computational checks, i.e., if the input data is sufficient for estimating productivity with one or more methodologies. If any of the logical checks are invalid, then the user is notified by a respective message, interrupting the data input and results generation process. If the problem appears during the computational checks, the user is again notified by a respective message and the estimation methodologies that created the computational error are de-selected automatically. The estimation process continues, and results are generated only for the methodologies with neitherout logical nor computational errors.

By selecting "Equipment" → "Projection," the form "MachineOpenForm" is activated which contains a multiple-page window, one for each type of equipment (Excavator, Loader, Truck) separately. Each user may select a predefined equipment, or add / edit and even delete any type of equipment and exit the menu. In a similar fashion, selecting "Operators" → "Projection" activates the form "OperatorOpenForm," including one window for the excavator operators and one for the loader operators. The user may edit or delete the operator's data (e.g., Name, Surname, social security data). Lastly, the menu "Assumptions" → "Productivity factors selection" activates the form "CoefficientForm," where the user may select the a productivity factor's preferred value: minimum, maximum, average, or random value between the minimum – maximum values.

5. Numerical Example

5.1. Case Description

This example case evaluates the developed automated system based on the operational analysis and productivity estimate process described in the previous sections. The case presents a productivity estimation of a hydraulic excavator JCB JS 200W (weight 23.200kg, Turbo engine 128kW, 1200 operating hours). It is equipped with a backhoe bucket (side area 0,88m2), length 1,25m, tooth width 0,98m (slightly used) and base width 0,95m. the maximum excavation depth is limited to 6,37m. The excavation pit is 52m above sea level, and the soil is cohesive (category IV according to DIN 18300:2012) and the excavation depth is 5m. The excavator deposits soil at a 45° angle from the excavation front under optimal working conditions. The operator has above-average skills and is in good psychological condition. Productivity factors have average values and the computational process has been executed for all fourteen estimation methodologies. For brevity reasons, only the computational process according to the BML (1983) methodology is presented in the following section and the reader is referred to Panas et al. (2022) for further details.

5.2. Excavator Operational Analysis - BML (1983) Estimation Methodology

The project data are as follows:

- Bucket capacity (V_{exc}): BML (1983) estimates bucket capacity according to the standards of the Committee for European Construction Equipment shown in Eq. (2):

$$V_{exc} = 0{,}96m^3 \tag{2}$$

- Cycle time (t_c): The cycle time depends on the bucket capacity and the soil category. For a 0,96m3 bucket and soil category IV, BML yields a cycle time estimate of Eq. (3):

$$t_c = 19s \tag{3}$$

- Swell factor (f_s): The swell factor for soil category IV equals to Eq. (4):

$$f_s = 1{,}19 \tag{4}$$

- Fill factor (f_{fill}): The fill factor for soil category IV equals to Eq. (5):

$$f_{fill} = 1{,}20 \tag{5}$$

- Swing factor (f_{swing}): The swing factor for a 45º angle equals to Eq. (6):

$$f_s = 1{,}08 \tag{6}$$

- Excavation depth factor (f_{depth}): the optimum excavation depth (h_{opt}) equals 1–2 times the bucket capacity, i.e. 0,96m < h_{opt} < 1,92m. Since the current excavation depth (5m) does not lie within that range, the excavation depth factor for a soil category IV is determined using Eq. (7):

$$f_{depth} = 0{,}83 \tag{7}$$

- Bucket dump factor (f_{dump}): Since the excavated soil is deposited freely, the bucket dump factor is equal to 1.
- Job efficiency factor (f_E): When working under optimum conditions, the job efficiency factor falls within the range 0,82–1,00. By taking the average of that range, it is determined using Eq. (8):

$$f_E = (0{,}82 + 1{,}00)/2 = 0{,}91 \tag{8}$$

As such, the effective productivity can be calculated using Eq. (9):

$$Q_{eff} = 3600 * (V_{exc}/t_c) * f_s * f_{fill} * f_{swing} * f_{depth} * f_{dump} * f_E = 3600*(0{,}96/19)*1{,}19*1{,}20*1{,}08*0{,}83*1{,}00*0{,}91 = 211{,}88 \text{ m}^3/\text{h} \tag{9}$$

5.3. Automated Tool Application

Selecting "New activity" and then "EXCAVATOR" from the dropdown equipment list initiates the system and presents all required fields for estimating productivity according to the predefined methodologies. The user selects "Average productivity values" from the field "Selection of productivity estimation methodologies" and presses the "Select all" button to load all available construction productivity estimation methodologies in the system. All data inputted is registered in the available fields, and the user presses the button "Calculate." The computational system will present all productivity estimation results (wherever feasible) in a list labeled "Productivity estimation results per methodology," as shown in Fig. 4.

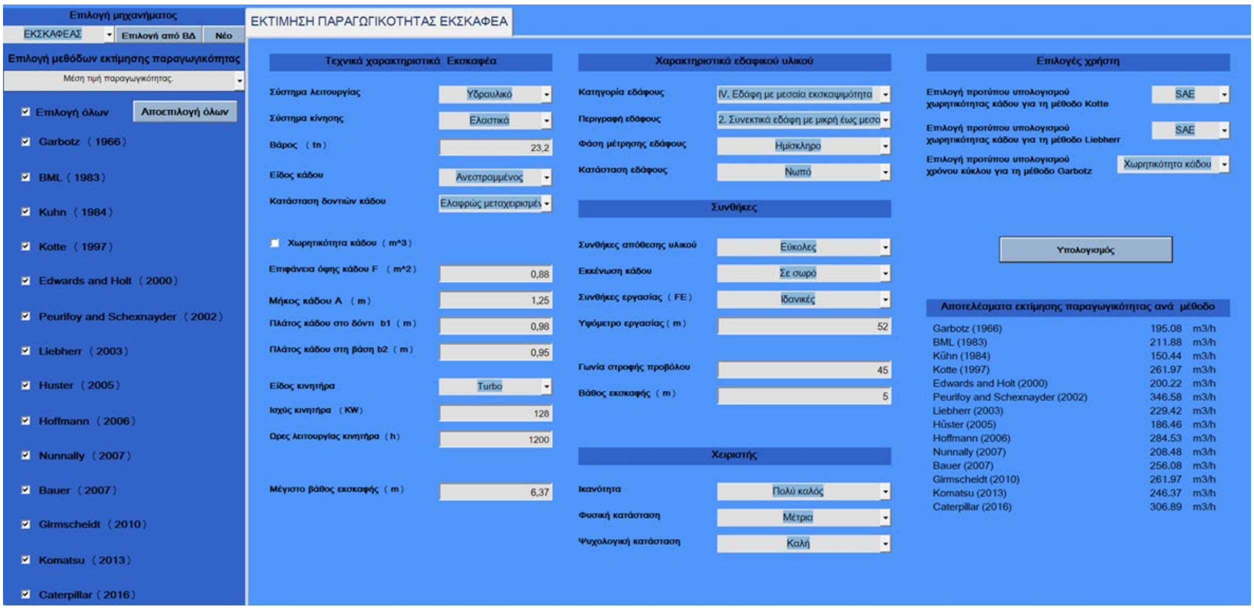


Fig. 4. Excavator productivity estimation form

Table 1. Case study comparative evaluation of productivity estimates

Productivity estimation methodologies	Excavator productivity estimation results [m3/h]	% Deviation from the average value	% Deviation from the lowest value
Kühn (1984)	150,44	−37,06%	0,00%
Hüster (2005)	186,46	−21,99%	23,94%
Garbotz (1966)	195,08	−18,39%	29,67%
Edwards and Holt (2000)	200,22	−16,24%	33,09%

Table 1. Case study comparative evaluation of productivity estimates (continued)

Productivity estimation methodologies	Excavator productivity estimation results [m3/h]	% Deviation from the average value	% Deviation from the lowest value
Nunnally (2007)	208,48	−12,78%	38,58%
BML (1983)	211,88	−11,36%	40,84%
Liebherr (2003)	229,42	−4,02%	52,50%
Komatsu (2013)	246,37	3,07%	63,77%
Bauer (2007)	256,08	7,13%	70,22%
Girmscheidt (2010)	261,97	9,60%	74,14%
Kotte (1997)	261,97	9,60%	74,14%
Hoffmann (2006)	284,53	19,04%	89,13%
Caterpillar (2019)	306,89	28,39%	103,99%
Peurifoy and Schexnayder (2002)	346,58	44,99%	130,38%
Average productivity value		239,03	

5.4. Comparative Evaluation of Productivity Estimates

The results presented in Table 1 prove there is a significant variability in the published methodologies' estimation predictability. The German contractors' association methodologies are generally more conservative than the ones in estimation handbooks. The latter is explained by the commercial nature of such publications that reflect optimum working conditions.

6. Discussion

The study's main inferences are summarized below:

- The developed automated tool yields robust and reliable productivity estimates. The provided estimates' validity reflects the system's adequate architectural structure.
- From a managerial point of view, the developed tool may not indicate the optimum estimate or a preferred solution. It provides possible outcomes given the set of user-input parameters. In other words, the estimator must choose the best solution, but has clear information on the quantitative implications.
- Any system's results are only as good as the validity and reliability of its input parameters. This is why testing the estimate methodologies' assumptions in an actual construction site setting is recommended. It is the most effective, efficient, and practical way to benchmark each methodology's association with a real case.
- The adopted approach may seem oversimplified due to its deterministic nature. However, construction practitioners worldwide still use the scrutinized methodologies. They are directly applicable and easily comprehensible despite their inflexible mathematical nature.
- The theoretical and empirical research presented in this paper must be placed in a scientific context that serves the estimator's needs for a practical approach to assess a specific operational scenario's on-site productivity. Of course, no tool can act as a panacea or substitute for the estimator's experience, but it can aid the decision-making process by providing critical project information.

7. Conclusions

This paper presented an automated tool for comparative estimates of earthmoving productivity, focusing on excavation operations. The developed system includes three modules (computational, data storage, and operational) and a series of forms enabling productivity estimates. All system components have been developed in a user-friendly MS environment. A numerical example corroborated the tool's validity. Possible future research may optimize the module integrated in the developed application to assist construction estimators make informed decisions when deploying critical project resources.

Author Contributions

Antonis Panas conceived the research and contributed to conceptualization, methodology, data collection and analysis, draft preparation, and manuscript editing. Nikos Kalaitzakis contributed to draft preparation, manuscript editing, and supervision. John-Paris Pantouvakis contributed to draft preparation, manuscript editing, and supervision. All authors have read and agreed with the manuscript before its submission and publication.

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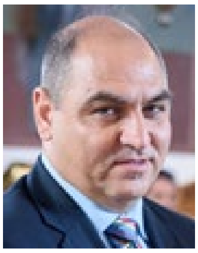

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